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Evaluation of Fuel Rod Performance by Statistical Approach

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1. Introduction

Fuel rod performance during steady-state operation and AOO can be affected by several uncertainties, and these are related to the initial dimension of fuel rod, models in computer code, and operating conditions[1]. Authors previous work showed the feasibility of the application of non-pararametric order statistics to the evaluation of combined uncertainties[2]. Typically root of sum of squares (RSS) method is also used for combining sources of errors in statistics. Thereby, two different statistical apparoachs mensioned above were employed to assess the rod performance in this study.

2. Analysis Details

Fuel rod performance up to 55 MWd/kgU was analyzed by use of FRPACON-3.4a audit code. The base case employed in this study utilized a 17x17 PWR fuel with Zircaloy-4 cladding, and the detailed information of rod dimension, power history and operating conditions can be found in Ref. [1]. AOO power pulse was prescribed such that the output power was increased 50% for a period of 4hrs at the fuel burnup of 30 MWd/kgU. Total 21 uncertainty parameters related to the manufacturing, model and power uncertainties were listed in Table 1.

Two different statistical approaches used for the assessment are root of sum of squares (RSS) and non-parametric order statistics. RSS method represented as follows.

$$P = P_{be} + Root\,\{\Sigma_i\,(P_i - P_{be})^{2}\}$$

For the non-parametric order statistics approach, the simple random sampling (SRS) technique is utilized [3]. Total 124 and 153 inputs were produced with the uncertainty combinations listed in Table 1. As 124 and 153 code runs have been performed, the third and the fourth highest values can be used as rod performance estimation with upper tolerance limit of 95% probability and 95% confidence level, respectively [4]. Sampling probability density function in the model and power uncertainty parameter was not known clearly in FRAPCON-3.4a code we assumed it as normal (case 1) and also as uniform (case 2).

3. Results

3.1 Sensitivity due to each uncertainty parameter

Table 2 shows the deviation of rod performance from the base case. In general, manufacturing uncertainties revealed a relatively small influence on the performance except for cladding inner diameter and thickness. In case of model uncertainties, however, fuel thermal conductivity and fuel thermal expansion showed the predominant influence on internal pressure, centerline temperature and cladding hoop strain. Rod internal pressure, oxide thickness and hydrogen content were also strongly affected by fission gas release (FGR), cladding corrosion and hydrogen pickup model, respectively. Power uncertainties during steady-state operation and AOO showed a moderate influence.

3.2 RSS approach

Table 3 shows the results of combined uncertainties of rod performance evaluated by the RSS method. When used RSS method, rod internal pressure and fuel centerline temperature increased from 12.9 MPa to 18.7 MPa and 2593.5 K to 2895.4 K, respectively. Hoop strain increment at the AOO also increased from 0.64 % to 0.83 %.

3.3 Non-parametric order statistics approach

Analysis results of non-parametric order statistics approach were listed in Table 3.

Table 1. Considered manufacturing, model and power uncertainties to the rod performance analysis

		Base	Tolerance or Bias	Probability density func.
Manufacturing	Cladding ID, mm	8.18	±0.04	Normal
	Cladding thickness, mm	0.610	±0.04	Normal
	Cladding roughness, microns	0.5	±0.3	Normal
	Pellet OD, mm	8.0	±0.013	Normal
	Pellet density(TD), %	95	±0.91	Normal
	Pellet re-sinter density, %	0.9	±0.4	Normal
	Pellet roughness, microns	2.0	±0.5	Normal
	Pellet dish diameter & depth, mm	4.01, 0.287	±0.5, +0.05	Normal
	Rod fill pressure, MPa	2.41	±0.07	Normal
	Rod plenum length, mm	254	±11.4	Normal
Model	Fuel thermal conductivity	0	±2σ	Normal, uniform
	Fuel thermal expansion	0	±2σ	Normal, uniform
	FGR	0	±2σ	Normal, uniform
	Cladding corrosion	0	±2σ	Normal, uniform
	Fuel swelling	0	±2σ	Normal, uniform
	Creep of cladding	0	±2σ	Normal, uniform
	Cladding axial growth	0	±2σ	Normal, uniform
	H pickup	0	±2σ	Normal, uniform
Power	Power(steady state), %	100	±2	Normal, uniform
	Power(AOO), %	150	±3	Normal, uniform
	Duration of AOO pulse, hr	4	±1	Normal, uniform

Table 2. Effects of each uncertainty parameter on the rod performance

		Rod internal pressure	Oxide thickness	Hydrogen content	Fuel centerline temp. at AOO	ΔHoop strain at AOO
Max. deviation from base case, max $\lvert P_i - P_{be}\rvert$		MPa	μm	ppm	K	%
Manufacturing	Cladding ID	0.85	0.0	21.1	6.3	0.003
	Cladding thickness	0.07	0.84	51.4	4.1	0.006
	Cladding roughness	0.05	0.0	0.0	5.9	0.004
	Pellet OD	0.20	0.07	0.6	0.1	0.001
	Pellet density(TD)	0.43	0.27	2.2	26.5	0.014
	Pellet re-sinter density	0.24	0.0	0.0	11.3	0.006
	Pellet roughness	0.11	0.0	0.0	10.4	0.007
	Pellet dish diameter & depth	0.20	0.0	0.0	0.4	0.012
	Rod fill pressure	0.25	0.0	0.0	0.9	0.001
	Rod plenum length	0.34	0.0	0.0	0.5	0.001
Model	Fuel thermal conductivity	4.17	0.0	0.0	295.7	0.145
	Fuel thermal expansion	0.21	0.0	0.0	0.7	0.127
	FGR	3.79	0.0	0.0	13.4	0.009
	Cladding corrosion	0.41	30.6	20.9	29.5	0.026
	Fuel swelling	0.07	0.0	0.0	0.1	0.000
	Creep of cladding	0.12	0.0	0.0	0.2	0.001
	Cladding axial growth	0.58	0.0	0.0	0.3	0.001
	H pickup	0.0	0.0	80	0.0	0.000
Power	Power(steady state)	0.54	0.29	2.4	-	-
	Power(AOO)	-	-		40.2	0.040
	Duration of AOO pulse	-	-		1.9	0.000

Table 3. Combined uncertainties to the rod rod performance

	Base case	RSS ([1]Δ%)	[2]SRS (case1)		[2]SRS (case2)	
			124 runs	153 runs	124 runs	153 runs
Rod internal pressure, MPa	12.9	18.7 (45.0)	16.6(28.7)	16.7(29.5)	18.8(45.7)	19.5(51.1)
Fuel centerline temp. at AOO, K	2593.5	2895.4 (11.6)	2813.1(8.5)	2778.5(7.1)	2918.1(12.5)	2874.5(9.8)
Hoop strain increment at AOO, %	0.64	0.83(31.7)	0.82(29.7)	0.81(27.8)	0.94(46.9)	0.92(43.8)

[1] Inside of ( ) means percent increase from the base case
[2] Sampling probability density function for the model and power parameter was assumed as normal (case 1) and uniform (case 2).

In case of 124 code runs with the normal distribution of sampling probability (case1), the rod internal pressure increased from 12.9 MPa to 16.6 MPa. Fuel centerline temperature and cladding hoop strain increment at the AOO also increased from 2593.5K to 2813.1K and from 0.64% to 0.82%, respectively. However the assessed combined uncertainties to the rod performance are smaller than the uncertainties evaluated by the RSS method. Meanwhile the combined uncertainty was not affected by the number of code runs.

When the sampling probability density function was assumed as uniform (case2), the combined uncertainty was increased as compared to the normal one (case1).

4. Summary

Fuel rod performance was evaluated by the two different statistical approaches. Following results can be drawn.

- Manufacturing and power uncertainties have a little or moderate influence on the rod performance. But related to the model, particularly fuel thermal conductivity and fuel thermal expansion model, showed significant impact.
- For the assessment of combined uncertainty to the rod performance, root of sum of squares (RSS) method gives a more conservative result than the non-parametric order statistics approach. But the sampling probability density function related to the model and power uncertainty is important to the performance assessment.

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